

## Micromanufacturing: Recent Developments in this Country and Abroad

Robert O. Warrington, Director      Craig R. Friedrich, Associate Professor  
Robert X. Gao, Research Associate      Gang Lin, Visiting Assistant Professor

**Institute for Micromanufacturing**  
**Louisiana Tech University**  
**Ruston, Louisiana 71272**  
**(318) 257-2357**

### Introduction

Often defined as an "emerging" technology, the microelectromechanical systems (MEMS) technologies have their roots in research activities back to the early 60s, as the first micro pressure sensors were fabricated using the anisotropic etching method [1]. Since then, the fabrication techniques developed in microelectronics have begun to directly impact the progress in micromechanics. During these years, pioneer research work in electrostatically-driven microstructures has been performed [2] which a decade later found its further development in surface micromachining for sensor formation [5].

During the 1970s, numerous industrial companies were involved in the efforts to commercialize the existing microfabrication technologies for a new generation of products featuring light weight, small volume and high efficiency. Among those pioneers, Texas Instruments succeeded in marketing micro printing elements in computer accessories and terminal products [3]. At the end of the 70s, the controlled anisotropic undercut etching technique was further developed which resulted in microcantilever beams and similar micromechanical structures.

The continuing exploitation of VLSI processing methods in the 1980s has opened considerable opportunities for the further invention of unique silicon-based micromechanical devices as well as the creation of new markets [4]. In response to the growing need for application specific integrated circuit chips (ASICs), custom design and fabrication facilities have been implemented. The concept of the "IC Foundry" quickly found its expression as the "Silicon Micromechanics Foundry" in the development and production of micromechanical structures [6]. Also during this time, based on a combination of deep-etch lithography and subsequent high-precision replication, a new micromachining technique, known as the "LIGA" process, was introduced in Germany for producing three dimensional microstructures [7]. Innovative improvement and modification to this process have subsequently been made by researchers at the University of Wisconsin [17]. Besides conventional electromagnetic actuators, various types of electrostatic motors and actuators featuring simple structure, micro size and high force/volume ratio were developed worldwide [8] - [11]. Also, different materials were investigated for possible applications in the micro robot domain, such as the shape memory alloy (SMA) [12].

Parallel to the endeavors of pushing ahead the micromanufacturing technique down to the order of submicron and nanometer scales, there have been numerous activities reported which focus on applying different micromachining technologies to fabricate end products which are mainly mini with microcomponents, such as the microcompact heat exchangers produced with diamond bit cutting [13]. To meet the increasing need for metrology and products inspection in the submicron and nano scale, atomic-force microscopes are under further development [14]. Also, micro EDM, molding, plating and many other new techniques are emerging to augment the microsensor and actuator fabrication [16]. It is evident that micromanufacturing technologies will lead to commercialization of revolutionary devices which will dramatically change our lives in the 21st century.

This paper will describe recent activities in high aspect ratio MEMS, the Louisiana initiatives in MEMS through the newly formed Institute for Micromanufacturing at Louisiana Tech University and their collaboration with the Center for Advanced Microstructures and Devices at Louisiana State University, and a brief discussion of MEMS activities in Russia.

### **The Louisiana Initiatives in MEMS**

The Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University was established in 1987 by a grant from the Department of Energy. The facility currently consists of an electron storage ring with a linac injector, two beam-lines which are under construction, and ancillary equipment. The Institute for Micromanufacturing (IfM) at Louisiana Tech University was established in 1991 by grants from the Department of Energy. This institute consists of a research building for multiple process micromachining, cleanrooms, process equipment, and state-of-the-art metrology and testing equipment. Additional equipment and line item funding for personnel, operating and supplies, for both facilities has been provided by the state of Louisiana. CAMD synchrotron is very close to being operational with the first beam-lines due to be installed shortly. The institute building is currently under architectural design and construction should start by late 1992 or early 1993. Staffing for both facilities is underway. A more complete description of CAMD and IfM are given below.

### **The Institute for Micromanufacturing**

The Institute for Micromanufacturing will be composed of three components. The focal point for the Institute for Micromanufacturing will be the component for research and development located on the Louisiana Tech University campus in Ruston. A second component will be associated with the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University in Baton Rouge. This component will perform research associated with the X-ray lithography micromachining capability at CAMD. The third and final component of the Institute is Technology Transfer. This component will be located in Shreveport/Bossier in order to take advantage of the unique opportunities and resources offered in this region. There will be a strong inter-

action among the three components of the proposed Institute and each of the components will interact, to varying degrees, with universities, industries and research centers within the state and region.

A major strength of the institute will be the complete integration of multiple process microtechnologies which will span the spectrum from nano to macro. Macro, mini, micro and nano are all a part of MEMS or micromanufacturing. An important component of the institute will be the development of minidevices with microcomponents requiring nanomeasurements with connections to the macroworld. These minidevices could very well become the economic drivers of the technology well into the next century.

### **Research and Development Component**

This component will consist of a new 40,000 sq. ft. building which will accommodate institute faculty, graduate students, visiting scientists and engineers. Almost 20,000 sq. ft. of laboratory space will include space for metrology and testing (2,700 sq. ft.), lithography (initially over 3,000 sq. ft. of class 1000 cleanroom space will be available, expandable to 5,500 sq. ft.), and alternative micromachining technologies such as energy beams. The entire floor of the laboratory area will be isolated from the structure and, in addition, many areas within the laboratory space will be isolated from the main floor pad. The laboratory bay will be kept at  $68 \pm 1$  °F and  $45 \pm 5\%$  relative humidity. Four areas of concentration will be developed within the facility at Louisiana Tech University. They are:

- \* The design and fabrication of microdevices, such as micro-motors, actuators, sensors, pumps, valves, and connectors.
- \* The design and fabrication of microstructures, such as micro-heat exchangers, filters, distillation columns and supports for micro-devices and systems.
- \* Research related directly to the manufacturing processes, including fabrication, metrology assembly and testing of the microproducts mentioned above.
- \* Microsystem research involving the integration of these microdevices/structures and interfacing of these systems with the macroworld.

Several technologies will be developed and used for the fabrication of these micro devices and structures. First, the existing capabilities in diamond bit machining at Louisiana Tech University will be enhanced. Micro electrical discharge machining capabilities are being acquired and power beam micromachining (excimer laser and focused ion beam) will be developed. Second, conventional photo lithography and chemical etch will be developed and used for the fabrication of low aspect ratio devices and structures. Third, as X-ray lithography technology becomes available at CAMD, Louisiana Tech and LSU researchers will utilize a dedicated beam line to fabricate high aspect ratio devices and structures. Finally, research and development will be

performed on small machines techniques that can build and assemble these microproducts.

### **X-ray Lithography Component and CAMD**

This component consists of a dedicated beam line (off of the electron storage ring at CAMD and associated equipment specifically for the fabrication of high aspect ratio structures and devices. Researchers from Louisiana Tech and Louisiana State University will work at CAMD on research directly related to the fabrication of microdevices and structures using selective etch techniques and the X-ray depth lithography available at CAMD. Direct communication with the component of the Institute in Ruston, will facilitate the design and fabrication of the structures and devices at the CAMD facility. This type of machining is currently available at only a few locations worldwide.

Of course, one of the key components of the institute will be the synchrotron light source. This electron storage ring has been optimized for soft X-ray lithography [15]. The CAMD storage ring has an energy of 1.2 GeV with 400 Ma circulating current. The ring can operate at 1.4 GeV with a decrease in circulating current to 200 Ma. The mean radius of the ring is 8.78 m with a circumference of 55.2 m. The ring has been designed with four straight sections, one of which is used for the 200 MeV low energy injection for the linac. The other three sections will be used for insertion devices such as undulators and wigglers.

The beamline for the micromachining application is currently being designed. Preliminary specifications for the line are that the line must transmit photons of 2 - 8.5 KeV and the high energy transmission must be less than 15% at 10 KeV. The photons must be incident vertically over a field of view of 50 mm horizontally with a uniformity of  $\pm 3\%$  and with a beam spot of less than 3 mm height. The beamline must be capable of exposing 100 micron thick 50 mm x 25 mm PMMA resists to a minimum of 4 kj/cc and a maximum of 20 kj/cc in less than 120 seconds with the CAMD storage ring being operated at nominal conditions. The beamline will have a calorimeter and beam position sensor which has a resolution of better than .05 mm for the vertical direction. The beryllium window must be of variable thickness and the transverse window size must be 10 mm x 50 mm. The beamline must be compatible for operation with a superconducting wiggler insertion device.

In addition to micromachining the following uses are anticipated for the facility:

- \* X-ray lithography for sub - .05 micron featured integrated circuits (the ring was optimized for this application).
- \* Electronic structure, surface science, etc.
- \* Geometrical structure, crystallography, etc.

- \* Imaging, microscopy, tomography, etc.
- \* Medical technology.
- \* Education of engineers, scientists and technicians.

### **Technology Transfer Component**

This facility is intended to help existing manufacturers obtain and use new and existing technologies to modernize their manufacturing processes and improve their productivity. Existence of such a facility should be helpful in attracting new industry as well. Staff members would conduct training at the facility or off-site, as needed, as well as using computer and video linkages to efficiently serve industry. In addition, they would seek to develop markets for existing products, look for new products to be developed.

Two facilities will be available for this activity. Space and limited conferencing facilities will be available at the research and development building on the Louisiana Tech University campus. A larger facility is being planned for Shreveport, Louisiana. This proposed facility of 30,000 sq. ft. will be used for conferencing, technology transfer and for close interaction with the Louisiana State University-Shreveport Biomedical Research Center.

### **MEMS Activities in Russia**

A United States-Russia forum on manufacturing, factories of the future, and productivity enhancement was held in St. Petersburg, Russia from 18 to 21 May, 1992. The first author presented a paper on micromanufacturing [18] and interacted with researchers interested in MEMS. In addition to this interaction, several universities and companies were visited in the St. Petersburg area. A follow-on trip to Moscow resulted in a visit and presentation to the recently formed Russian Academy of Sciences (includes engineering and everything else). Several general observations from this visit listed are: 1) the status of MEMS in the United States is not well known in Russia (the reverse is also true); 2) the status of MEMS research in Russia does not seem to be well known by researchers in Russia, particularly what is being done in defense related industries - this is just now becoming available and it appears that everything is opening up; 3) the Russian researchers are eager to collaborate and have initiated some collaborations, particularly with Europe; 4) until the economy stabilizes, their resources (for travel, operating, etc.) appear to be very limited; 5) their higher educational system and structure is currently undergoing major review and it appears that the revisions which will be implemented will incorporate both the US and European (particularly German) systems; and 6) the Russian Academy of Sciences is extremely sensitive and worried about the movement of scientists and bright students from Russia to other parts of the world.

There appears to be considerable activities in MEMS throughout Russia, however, several scientists felt that this was a small field of activity. MEMS interest appeared to be mostly focused on sensors, optics, acoustics, and materials. None of the researchers that were contacted knew of research in micro gears, motors, or systems, however most were interested in extending their work into these areas. Several robotics researchers attended the workshop and indicated that they were interested in micro-robots, although none knew of any current research activities in this area. Listed below are a few current MEMS activities from one large microelectronics firm and one university research center.

- \* Avangard (microelectronics company outside of St. Petersburg)
  - Ion sensor (ion-sensitive field effect transistor), chip size 5 x 1 mm.
  - Multiple gas sensor on chip (up to three) with local calorimetric control and heater temperature control.
  - Acoustoelectronic devices with reflector arrays.
  - Approximately 35,000 sq. ft. of class 1000 (?) cleanroom space.
  
- \* Scientific-Educational Center of Microtechnology and Testing (St. Petersburg Electrical Engineering Institute)
  - Bio crystals of phospholipid analogues for sensors and molecular electronics micro actuators.
  - Starting to investigate micromechanical device fabrication.

These facilities were in relatively good shape. Processing equipment used 2-3 inch wafer technology and most of the equipment was of Russian origin. The laboratories were well maintained, however, the cleanrooms were not of high quality. It appears that the many Russian microelectronic industries are not competitive for VLSI but could be very competitive in MEMS.

### Summary

This paper has attempted to summarize some recent activities in this country and overseas. The effort in Louisiana is relatively new and growing. The Russian effort is not well coordinated or documented. A conference on Micro Systems Technologies is scheduled for June of 1993 in St. Petersburg, Russia. Serious consideration should be given to developing a strategy to not only participate in this meeting, but also to spend additional time in Russia assessing the technology. MEMS technologies will eventually affect virtually every aspect of our lives and, at least in the near term, mini devices with micro components will probably be the economic drivers for the technology.

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## **MICROSENSORS AND MICROINSTRUMENTS: NEW MEASUREMENT PRINCIPLES AND NEW APPLICATIONS\***

**W. J. Kaiser, T. R. VanZandt, T. W. Kenny, W. B. Banerdt, and D. Crisp**  
**Center for Space Microelectronics Technology**  
**Jet Propulsion Laboratory, California Institute of Technology**  
**Pasadena, California 91109**

### **ABSTRACT**

An important new approach for space science is based on the use of compact, low-mass, low-cost science instruments integrated with their delivery systems. Many advantages of this approach lead to new missions and new science return opportunities. First, many critical investigations of planetary interiors, surfaces, and atmospheres, which require in-situ measurements, may be completed, since the cost in resources to execute in-situ science is reduced. Second, the reduced mass and volume of microinstrument systems allow a greatly expanded distribution of measurement sites. Then, science investigations may be performed simultaneously over large regions. In particular, a major advance in the investigation of planetary interior structure by seismology or atmospheric properties by meteorology is obtained by use of a planetary-wide measurement network.

Advances in microelectronics have enabled the convenient fabrication of compact structures (for example, by silicon micromachining). Many advantages of this approach provide new capabilities for producing sensors and instruments for guidance and control, seismology, meteorology, material and gas analysis, and other in-situ science applications. However, the development of compact sensors and instruments leads to a variety of fundamental sensor sensitivity limits. In particular, the development of compact instruments for many of the most important applications requires a drastic improvement in signal detection sensitivity. Thus, new fabrication techniques may not, alone, yield suitable microinstruments. Instead, improved measurement methods must be developed to enable microsensors and microinstruments. In this presentation, the unique challenges for microsensor and microinstrument technology will be discussed.

Recent developments at JPL, based on novel signal detection principles, have produced a series of ultra-high sensitivity microsensors and microinstruments. Included among the applications demonstrated are a micro-seismometer, micro-accelerometer, micro-magnetometer and a unique, uncooled infrared detector. Also in this presentation, the principles, performance, and unique in-situ science applications of these new devices will be described. It will be shown that the implementation of microinstruments using these principles produces systems having performance equivalent to previous conventional instruments, but, with major reductions in mass, volume, and power consumption.

\* Research supported by NASA, DARPA, NADC, ONT, ASTRO, and SDIO/IST.



Micro-Sensors, -Actuators, and -Systems:  
Accomplishments and Prospects

Richard M. White  
Co-Director, Berkeley Sensor & Actuator Center

and

Professor, Department of Electrical Engineering and  
Computer Sciences  
University of California  
Berkeley, CA 94720

Microsensors and microactuators have been reported in recent years by many researchers worldwide. Most are made with silicon by integrated-circuit processing techniques, often augmented by specialized etching (bulk or surface micromachining), or by electroplating, as in the LIGA and related processes. Deposited films have been used as micromechanical members (examples being polycrystalline silicon and low-stress silicon nitride), or as actuators (such as the thin-film piezoelectrics zinc oxide and lead-zirconate-titanate, and shape-memory alloy thin films). Techniques for bonding together individual die have been developed, and some polymeric structures have been reported. In many cases, integrated circuitry has been included on the sensor/actuator die for signal conditioning, control, test and calibration purposes.

Other devices that have emerged from this work include a microlamp having a gas-tight enclosure, and ultrasonic devices that transport granular solids, pump and mix fluids, measure viscosity, and function as gravimetric sensors for chemical gases and certain biomolecules in liquids. An important indication of the maturity of the field was the 1991 announcement by Analog Devices of its accelerometer, which employs a micromechanical sensing element and much associated integrated circuitry.

One may expect in the future to see: more integrated microsystems having increased functionality; emergence of CAD tools for the entire design of these devices; use of the fabrication techniques developed to make critical parts of milli- and mini-, instead of micro-, devices; expansion into systems that accomplish chemical and biological analysis, and even synthesis; and greater use of optical interactions with these devices.



## National Nanofabrication Facility and Nanoelectromechanics

Noel C. MacDonald  
School of Electrical Engineering and  
The National Nanofabrication Facility  
Cornell University  
Ithaca, NY 14853-5401

The National Nanofabrication Facility at Cornell University (NNF) is a partnership formed by Cornell University, the National Science Foundation, university and government laboratories, and leading American corporations. The NNF mission is to advance the fabrication capabilities at dimensions less than 100 nm (nanofabrication), and advance the applications of micro- and nanofabrication to diverse areas of science and engineering applications.

NNF has become a national focal point for teaching and research in nanofabrication. A sophisticated laboratory facility with complete instrumentation for fabricating structures at submicrometer and nanometer dimensions, NNF provides an ideal hands-on environment for graduate students conducting state-of-the-art thesis research and for industrial scientists and engineers pursuing emerging technologies.

We have developed a nanoelectromechanical scanned probe mechanism using an integrated, single crystal silicon (SCS) process. Suspended SCS structures are used to fabricate x-y capacitive translators and high aspect ratio conical tips for scanned probe devices. The integrated nano-mechanical device includes methods to form integrated tunneling tip pairs and to produce electrical isolation, contacts, and conductors. Each device occupies a nominal area of  $40\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$ . These devices include a novel self-aligned tip-above-a-tip tunneling structure and capacitive x-y translators defined by electron beam lithography and the thermal oxidation of silicon. The x-y translators produce a maximum x-y displacement of  $\pm 200\text{ nm}$  for an applied voltage of 55V. The low mass ( $2 \times 10^{-13}\text{ kg}$ ), rigid structure has a measured fundamental mechanical resonant frequency of 5 MHz.

THE UNITED STATES OF AMERICA  
DO hereby certify that the following is a true and correct copy of the original as the same appears in the records of the Department of the Interior.

IN WITNESS WHEREOF, the Secretary of the Interior has hereunto set his hand and the seal of the Department of the Interior at Washington, D. C., this 1st day of January, 1901.

JOHN W. FOSTER, Secretary of the Interior.

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